

Analyzing changes in the complexity of climate in the last four decades using MERRA-2 radiation data

Supplementary Material

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1- Momentum Statistics

| SW | Mean | Variance | Skewness | Kurtosis |
|--------------------------------------|--------------------------|-----------------------|------------------------|--------------------------|
| FIT | 103.332 + 0.0998342*x | 29.097 + 0.38949*x | 0.0935 + 0.004044*x | -0.6754 + 0.0004639*x |
| Intercept | 103.332 | 29.097 | 0.0935 | -0.6754 |
| σ_Intercept | 0.304571 | 1.0622 | 0.03711 | 0.04788 |
| X Intercept | -1035.04 | -74.705 | -23.12 | 1456 |
| Slope | 0.0998342 | 0.38949 | 0.004044 | 0.0004639 |
| σ_Slope | 0.013614 | 0.047479 | 0.001659 | 0.00214 |
| Correlation | 0.778298 | 0.81109 | 0.381 | 0.03662 |
| R² | 0.605748 | 0.65787 | 0.1452 | 0.001341 |
| σ | 0.883207 | 3.0802 | 0.1076 | 0.1388 |
| s for residual | 0.895063 | 3.1215 | 0.1091 | 0.1407 |
| Sample Size | 38 | 38 | 38 | 38 |

Table A.1 – Momentum statistics table for short-wave radiation data from 1980-2017.

| LW | Mean | Variance | Skewness | Kurtosis |
|--------------------------------------|------------------------|------------------------|--------------------------|---------------------------|
| FIT | 237.46 + 0.021439*x | 6.9047 - 0.017996*x | 0.29496 - 0.0011717*x | -0.70326 + 0.0030776*x |
| Intercept | 237.46 | 6.9047 | 0.29496 | -0.70326 |
| σ_Intercept | 0.17769 | 0.42193 | 0.049873 | 0.076969 |
| X Intercept | -11076 | 383.69 | 251.74 | 228.51 |
| Slope | 0.021439 | -0.017996 | -0.0011717 | 0.0030776 |
| σ_Slope | 0.0079425 | 0.01886 | 0.0022293 | 0.0034404 |
| Correlation | 0.4151 | -0.15923 | -0.08849 | 0.1495 |
| R² | 0.17231 | 0.025354 | 0.0078305 | 0.022351 |
| σ | 0.51527 | 1.2235 | 0.14463 | 0.2232 |
| s for residual | 0.52218 | 1.24 | 0.14657 | 0.22619 |
| Sample Size | 38 | 38 | 38 | 38 |

Table A.2 – Momentum statistics table for long-wave radiation data from 1980-2017.

2- ApEn and SampEn Results

| | ApEn SW | ApEn LW | SampEn SW | SampEn LW |
|--------------------------------------|-------------------------|------------------------|-------------------------|--------------------------|
| FIT | 1.9609 - 0.0018711*x | 1.462 - 0.0010405*x | 1.9796 - 5.929e-11*x | 1.4724 - 3.2972e-11*x |
| Intercept | 1.9609 | 1.462 | 1.9796 | 1.4724 |
| σ_Intercept | 0.013524 | 0.0040316 | 0.019202 | 0.0057245 |
| X Intercept | 1048 | 1405 | 3.3389e10 | 4.4656e10 |
| Slope | -0.0018711 | -0.0010405 | -5.929e-11 | -3.2972e-11 |
| σ_Slope | 0.00062884 | 0.00018746 | 1.9927e-11 | 5.9404e-12 |
| Correlation | -0.44932 | -0.68421 | -0.44931 | -0.68421 |
| R² | 0.20188 | 0.46815 | 0.20188 | 0.46814 |
| σ | 0.040796 | 0.012162 | 0.040796 | 0.012162 |
| s for residual | 0.041343 | 0.012325 | 0.041343 | 0.012325 |
| Sample Size | 38 | 38 | 38 | 38 |

Table A.3 – ApEn and SampEn fit table for long-wave radiation data from 1980-2017 for $m = 2$.

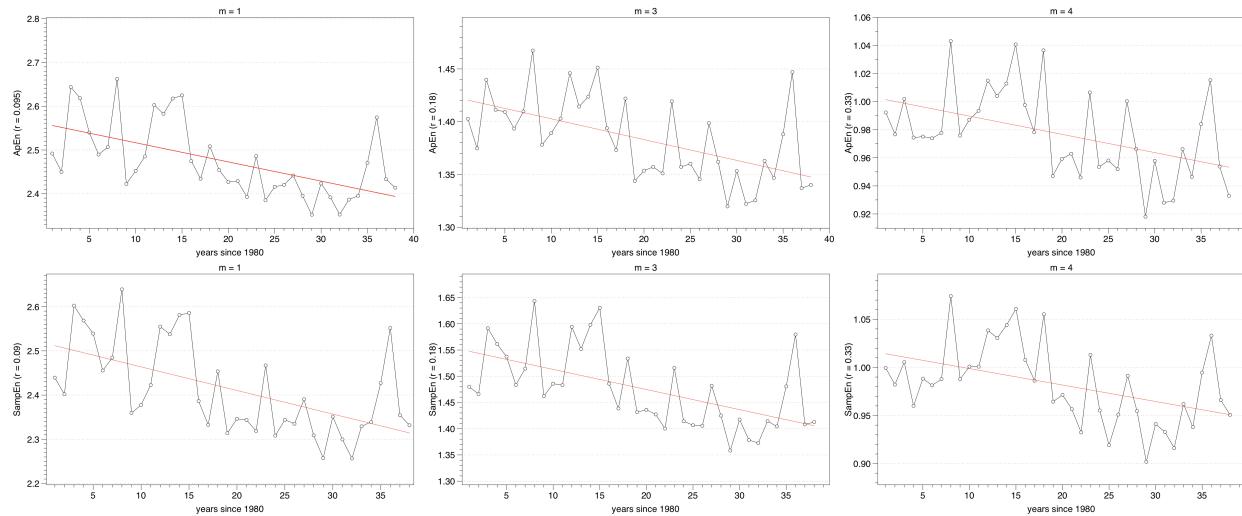


Figure A.1 – ApEn and SampEn for SW radiation from 1980-2017 using different values of the embedding dimension $m = 1, 3$, and 4 to confirm the trend

3- Mutual Information Results

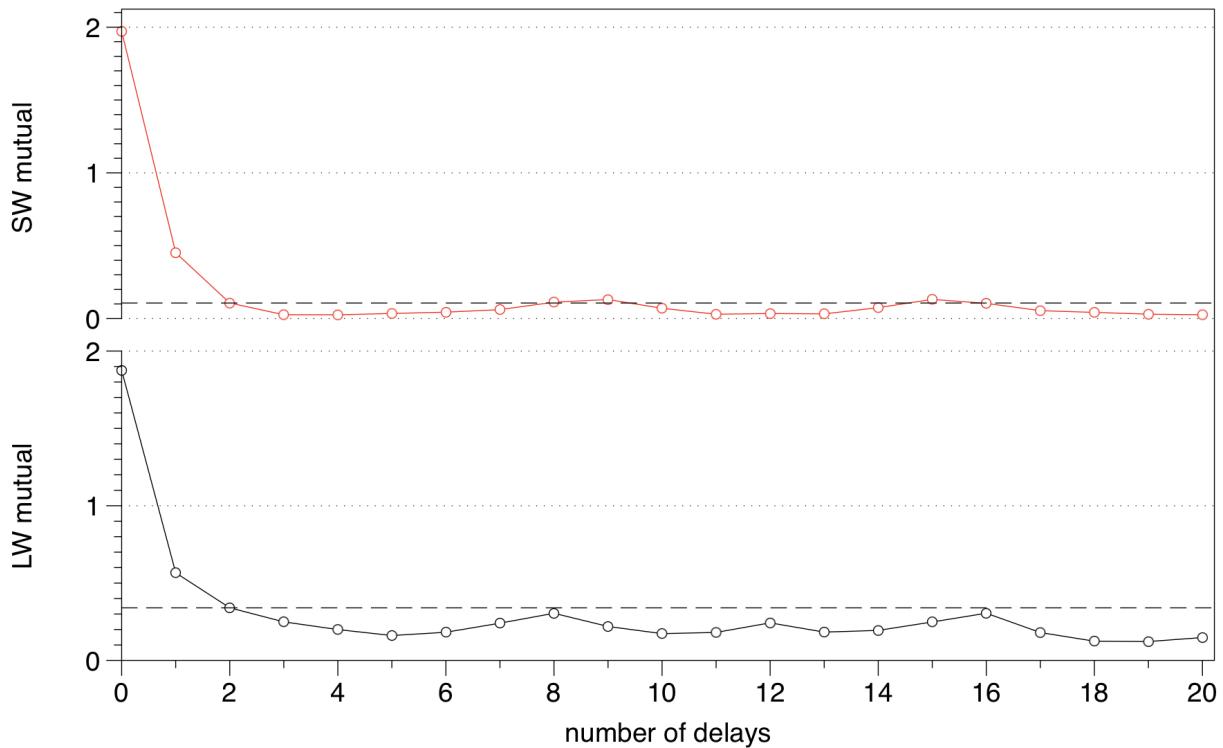


Figure A.2 – Mutual Information analysis for short- and long-wave radiation.

Mutual information is calculated as:

$$M_{\{I,J\}} = \sum p(i,j) \log \frac{p(i,j)}{p(i)p(j)}$$

We compare the series of short-wave (Figure A.2 - top) and long-wave (Figure A.2 - bottom) radiation with lagged versions of themselves. If the considered number of delays is insufficient, then the results of the Transfer Entropy analysis may be based on previous results of the series, instead of information flux from other series. If the number of delays is too large, we are introducing useless information which may be considered as transference of information which is not due to the dynamics and decrease the statistical significance of the Transfer Entropy results. We select a number of lags of two for both series (the two previous hours have influence in the prediction of the next value). The gain of information by adding more delays is minimal and basically independent of the number of delays.

4- Transfer Entropy Results

4.1 – Effective Transfer Entropy four decades fit

| | SW to LW | LW to SW |
|--------------------------------------|----------------------------|--------------------------|
| FIT | 0.019111 - 0.00027216*x | 0.004593 + 6.795e-6*x |
| Intercept | 0.019111 | 0.004593 |
| σ Intercept | 0.0015573 | 0.0005856 |
| X Intercept | 70.22 | -675.9 |
| Slope | -0.00027216 | 6.795e-6 |
| σ Slope | 7.2414e-5 | 2.723e-5 |
| Correlation | -0.53623 | 0.04214 |
| R² | 0.28754 | 0.001776 |
| σ | 0.0046979 | 0.001767 |
| s for residual | 0.0047609 | 0.00179 |
| Sample Size | 38 | 38 |

Table A.4 – Fit of ETE between short- and long-wave radiation.

4.2 –Yearly Transfer Entropy calculations

"1980-01-01 GMT" to "1980-12-31 GMT"

Shannon's entropy on 8 cores with 100 shuffles.

x and y have length 8783 (0 NAs removed)

[calculate] X->Y transfer entropy

[calculate] Y->X transfer entropy

[bootstrap] 300 times

Done - Total time 25.75 seconds

Shannon Transfer Entropy Results:

| Direction | TE | Eff. TE | Std.Err. | p-value | sig |
|-----------|--------|---------|----------|---------|-----|
| X->Y | 0.0192 | 0.0150 | 0.0007 | 0.0000 | *** |
| Y->X | 0.0085 | 0.0047 | 0.0007 | 0.0000 | *** |

Bootstrapped TE Quantiles (300 replications):

| Direction | 0% | 25% | 50% | 75% | 100% |
|-----------|----|-----|-----|-----|------|
|-----------|----|-----|-----|-----|------|

X->Y 0.0031 0.0045 0.0048 0.0053 0.0070

Y->X 0.0024 0.0040 0.0045 0.0050 0.0072

Number of Observations: 8783

p-values: < 0.001 '***', < 0.01 '**', < 0.05 *', < 0.1 .'

"1981-01-01 GMT" to "1981-12-31 GMT"

Shannon's entropy on 8 cores with 100 shuffles.

x and y have length 8760 (0 NAs removed)

[calculate] X->Y transfer entropy

[calculate] Y->X transfer entropy

[bootstrap] 300 times

Done - Total time 25.68 seconds

Shannon Transfer Entropy Results:

| Direction | TE | Eff. TE | Std.Err. | p-value | sig |
|-----------|--------|---------|----------|---------|-----|
| X->Y | 0.0189 | 0.0146 | 0.0007 | 0.0000 | *** |
| Y->X | 0.0103 | 0.0066 | 0.0008 | 0.0000 | *** |

Bootstrapped TE Quantiles (300 replications):

| Direction | 0% | 25% | 50% | 75% | 100% |
|-----------|--------|--------|--------|--------|--------|
| X->Y | 0.0034 | 0.0045 | 0.0049 | 0.0054 | 0.0083 |
| Y->X | 0.0032 | 0.0042 | 0.0046 | 0.0050 | 0.0066 |

Number of Observations: 8760

p-values: < 0.001 '***', < 0.01 '**', < 0.05 *', < 0.1 '.'

"1982-01-01 GMT" to "1982-12-31 GMT"

Shannon's entropy on 8 cores with 100 shuffles.

x and y have length 8760 (0 NAs removed)

[calculate] X->Y transfer entropy

[calculate] Y->X transfer entropy

[bootstrap] 300 times

Done - Total time 25.56 seconds

Shannon Transfer Entropy Results:

| Direction | TE | Eff. TE | Std.Err. | p-value | sig |
|-----------|--------|---------|----------|---------|-----|
| X->Y | 0.0165 | 0.0122 | 0.0007 | 0.0000 | *** |
| Y->X | 0.0081 | 0.0039 | 0.0008 | 0.0000 | *** |

Bootstrapped TE Quantiles (300 replications):

| Direction | 0% | 25% | 50% | 75% | 100% |
|-----------|--------|--------|--------|--------|--------|
| X->Y | 0.0031 | 0.0045 | 0.0050 | 0.0055 | 0.0076 |
| Y->X | 0.0030 | 0.0043 | 0.0046 | 0.0052 | 0.0070 |

Number of Observations: 8760

p-values: < 0.001 '***', < 0.01 '**', < 0.05 *', < 0.1 '.'

"1983-01-01 GMT" to "1983-12-31 GMT"

Shannon's entropy on 8 cores with 100 shuffles.

x and y have length 8760 (0 NAs removed)

[calculate] X->Y transfer entropy

[calculate] Y->X transfer entropy

[bootstrap] 300 times

Done - Total time 24.97 seconds

Shannon Transfer Entropy Results:

| Direction | TE | Eff. TE | Std.Err. | p-value | sig |
|-----------|--------|---------|----------|---------|-----|
| X->Y | 0.0335 | 0.0292 | 0.0008 | 0.0000 | *** |
| Y->X | 0.0094 | 0.0057 | 0.0008 | 0.0000 | *** |

Bootstrapped TE Quantiles (300 replications):

| Direction | 0% | 25% | 50% | 75% | 100% |
|-----------|--------|--------|--------|--------|--------|
| X->Y | 0.0031 | 0.0047 | 0.0053 | 0.0059 | 0.0079 |
| Y->X | 0.0029 | 0.0042 | 0.0048 | 0.0054 | 0.0077 |

Number of Observations: 8760

p-values: < 0.001 '***', < 0.01 '**', < 0.05 *', < 0.1 '.'

"1984-01-01 GMT" to "1984-12-31 GMT"

Shannon's entropy on 8 cores with 100 shuffles.

x and y have length 8784 (0 NAs removed)

[calculate] X->Y transfer entropy

[calculate] Y->X transfer entropy

[bootstrap] 300 times

Done - Total time 24.94 seconds

Shannon Transfer Entropy Results:

| Direction | TE | Eff. TE | Std.Err. | p-value | sig |
|-----------|--------|---------|----------|---------|-----|
| X->Y | 0.0245 | 0.0203 | 0.0008 | 0.0000 | *** |
| Y->X | 0.0104 | 0.0065 | 0.0008 | 0.0000 | *** |

Bootstrapped TE Quantiles (300 replications):

| Direction | 0% | 25% | 50% | 75% | 100% |
|-----------|--------|--------|--------|--------|--------|
| X->Y | 0.0032 | 0.0043 | 0.0048 | 0.0053 | 0.0088 |
| Y->X | 0.0031 | 0.0041 | 0.0046 | 0.0052 | 0.0068 |

Number of Observations: 8784

p-values: < 0.001 ***!, < 0.01 **!, < 0.05 *!, < 0.1 !

"1985-01-01 GMT" to "1985-12-31 GMT"

Shannon's entropy on 8 cores with 100 shuffles.

x and y have length 8760 (0 NAs removed)

[calculate] X->Y transfer entropy

[calculate] Y->X transfer entropy

[bootstrap] 300 times

Done - Total time 24.9 seconds

Shannon Transfer Entropy Results:

| Direction | TE | Eff. TE | Std.Err. | p-value | sig |
|-----------|--------|---------|----------|---------|-----|
| X->Y | 0.0212 | 0.0168 | 0.0007 | 0.0000 | *** |
| Y->X | 0.0090 | 0.0050 | 0.0008 | 0.0033 | ** |

Bootstrapped TE Quantiles (300 replications):

| Direction | 0% | 25% | 50% | 75% | 100% |
|-----------|--------|--------|--------|--------|--------|
| X->Y | 0.0031 | 0.0045 | 0.0050 | 0.0055 | 0.0096 |
| Y->X | 0.0027 | 0.0040 | 0.0045 | 0.0049 | 0.0065 |

Number of Observations: 8760

p-values: < 0.001 ***!, < 0.01 **!, < 0.05 *!, < 0.1 !

"1986-01-01 GMT" to "1986-12-31 GMT"

Shannon's entropy on 8 cores with 100 shuffles.

x and y have length 8760 (0 NAs removed)

[calculate] X->Y transfer entropy

[calculate] Y->X transfer entropy

[bootstrap] 300 times

Done - Total time 24.9 seconds

Shannon Transfer Entropy Results:

| Direction | TE | Eff. TE | Std.Err. | p-value | sig |
|-----------|--------|---------|----------|---------|-----|
| X->Y | 0.0165 | 0.0123 | 0.0007 | 0.0000 | *** |
| Y->X | 0.0103 | 0.0066 | 0.0008 | 0.0000 | *** |

Bootstrapped TE Quantiles (300 replications):

| Direction | 0% | 25% | 50% | 75% | 100% |
|-----------|----|-----|-----|-----|------|
| | | | | | |

X->Y 0.0031 0.0045 0.0051 0.0056 0.0079
Y->X 0.0029 0.0042 0.0047 0.0052 0.0068

Number of Observations: 8760

p-values: < 0.001 ***!, < 0.01 **!, < 0.05 *!, < 0.1 !.

"1987-01-01 GMT" to "1987-12-31 GMT"

Shannon's entropy on 8 cores with 100 shuffles.

x and y have length 8760 (0 NAs removed)

[calculate] X->Y transfer entropy

[calculate] Y->X transfer entropy

[bootstrap] 300 times

Done - Total time 24.98 seconds

Shannon Transfer Entropy Results:

| Direction | TE | Eff. TE | Std.Err. | p-value | sig |
|-----------|--------|---------|----------|---------|-----|
| X->Y | 0.0218 | 0.0175 | 0.0008 | 0.0000 | *** |
| Y->X | 0.0083 | 0.0042 | 0.0008 | 0.0000 | *** |

Bootstrapped TE Quantiles (300 replications):

| Direction | 0% | 25% | 50% | 75% | 100% |
|-----------|--------|--------|--------|--------|--------|
| X->Y | 0.0033 | 0.0044 | 0.0050 | 0.0054 | 0.0082 |
| Y->X | 0.0030 | 0.0041 | 0.0046 | 0.0053 | 0.0070 |

Number of Observations: 8760

p-values: < 0.001 ***!, < 0.01 **!, < 0.05 *!, < 0.1 !.

"1988-01-01 GMT" to "1988-12-31 GMT"

Shannon's entropy on 8 cores with 100 shuffles.

x and y have length 8784 (0 NAs removed)

[calculate] X->Y transfer entropy

[calculate] Y->X transfer entropy

[bootstrap] 300 times

Done - Total time 25.16 seconds

Shannon Transfer Entropy Results:

| Direction | TE | Eff. TE | Std.Err. | p-value | sig |
|-----------|--------|---------|----------|---------|-----|
| X->Y | 0.0205 | 0.0162 | 0.0007 | 0.0000 | *** |
| Y->X | 0.0105 | 0.0065 | 0.0008 | 0.0000 | *** |

Bootstrapped TE Quantiles (300 replications):

Direction 0% 25% 50% 75% 100%

X->Y 0.0032 0.0045 0.0050 0.0056 0.0072
Y->X 0.0029 0.0041 0.0045 0.0049 0.0077

Number of Observations: 8784

p-values: < 0.001 ***!, < 0.01 **!, < 0.05 *!, < 0.1 !!

"1989-01-01 GMT" to "1989-12-31 GMT"

Shannon's entropy on 8 cores with 100 shuffles.
x and y have length 8760 (0 NAs removed)
[calculate] X->Y transfer entropy
[calculate] Y->X transfer entropy
[bootstrap] 300 times
Done - Total time 26.65 seconds
Shannon Transfer Entropy Results:

| Direction | TE | Eff. TE | Std.Err. | p-value | sig |
|-----------|--------|---------|----------|---------|-----|
| X->Y | 0.0250 | 0.0205 | 0.0007 | 0.0000 | *** |
| Y->X | 0.0058 | 0.0019 | 0.0007 | 0.1633 | |

Bootstrapped TE Quantiles (300 replications):

| Direction | 0% | 25% | 50% | 75% | 100% |
|-----------|--------|--------|--------|--------|--------|
| X->Y | 0.0034 | 0.0045 | 0.0051 | 0.0055 | 0.0076 |
| Y->X | 0.0034 | 0.0043 | 0.0048 | 0.0052 | 0.0069 |

Number of Observations: 8760

p-values: < 0.001 ***!, < 0.01 **!, < 0.05 *!, < 0.1 !!

"1990-01-01 GMT" to "1990-12-31 GMT"

Shannon's entropy on 8 cores with 100 shuffles.
x and y have length 8760 (0 NAs removed)
[calculate] X->Y transfer entropy
[calculate] Y->X transfer entropy
[bootstrap] 300 times
Done - Total time 25.94 seconds
Shannon Transfer Entropy Results:

| Direction | TE | Eff. TE | Std.Err. | p-value | sig |
|-----------|--------|---------|----------|---------|-----|
| X->Y | 0.0239 | 0.0194 | 0.0007 | 0.0000 | *** |
| Y->X | 0.0078 | 0.0041 | 0.0008 | 0.0033 | ** |

Bootstrapped TE Quantiles (300 replications):

Direction 0% 25% 50% 75% 100%

X->Y 0.0032 0.0044 0.0048 0.0053 0.0081

Y->X 0.0031 0.0042 0.0048 0.0054 0.0069

Number of Observations: 8760

p-values: < 0.001 ***!, < 0.01 **!, < 0.05 *!, < 0.1 !

"1991-01-01 GMT" to "1991-12-31 GMT"

Shannon's entropy on 8 cores with 100 shuffles.

x and y have length 8760 (0 NAs removed)

[calculate] X->Y transfer entropy

[calculate] Y->X transfer entropy

[bootstrap] 300 times

Done - Total time 26.32 seconds

Shannon Transfer Entropy Results:

Direction TE Eff. TE Std.Err. p-value sig

X->Y 0.0169 0.0126 0.0008 0.0000 ***

Y->X 0.0062 0.0024 0.0008 0.0900 .

Bootstrapped TE Quantiles (300 replications):

Direction 0% 25% 50% 75% 100%

X->Y 0.0032 0.0045 0.0050 0.0056 0.0077

Y->X 0.0030 0.0044 0.0049 0.0054 0.0080

Number of Observations: 8760

p-values: < 0.001 ***!, < 0.01 **!, < 0.05 *!, < 0.1 !

"1992-01-01 GMT" to "1992-12-31 GMT"

Shannon's entropy on 8 cores with 100 shuffles.

x and y have length 8784 (0 NAs removed)

[calculate] X->Y transfer entropy

[calculate] Y->X transfer entropy

[bootstrap] 300 times

Done - Total time 25.43 seconds

Shannon Transfer Entropy Results:

Direction TE Eff. TE Std.Err. p-value sig

X->Y 0.0230 0.0186 0.0008 0.0000 ***

Y->X 0.0065 0.0025 0.0009 0.1100

Bootstrapped TE Quantiles (300 replications):

Direction 0% 25% 50% 75% 100%

X->Y 0.0035 0.0048 0.0052 0.0059 0.0078

Y->X 0.0027 0.0043 0.0047 0.0053 0.0078

Number of Observations: 8784

p-values: < 0.001 ***!, < 0.01 **!, < 0.05 *!, < 0.1 !.

"1993-01-01 GMT" to "1993-12-31 GMT"

Shannon's entropy on 8 cores with 100 shuffles.

x and y have length 8760 (0 NAs removed)

[calculate] X->Y transfer entropy

[calculate] Y->X transfer entropy

[bootstrap] 300 times

Done - Total time 26.73 seconds

Shannon Transfer Entropy Results:

| Direction | TE | Eff. TE | Std.Err. | p-value | sig |
|-----------|----|---------|----------|---------|-----|
|-----------|----|---------|----------|---------|-----|

| | | | | | |
|------|--------|--------|--------|--------|-----|
| X->Y | 0.0232 | 0.0189 | 0.0008 | 0.0000 | *** |
|------|--------|--------|--------|--------|-----|

| | | | | | |
|------|--------|--------|--------|--------|-----|
| Y->X | 0.0097 | 0.0050 | 0.0009 | 0.0000 | *** |
|------|--------|--------|--------|--------|-----|

Bootstrapped TE Quantiles (300 replications):

Direction 0% 25% 50% 75% 100%

X->Y 0.0034 0.0052 0.0058 0.0064 0.0085

Y->X 0.0031 0.0043 0.0048 0.0054 0.0070

Number of Observations: 8760

p-values: < 0.001 ***!, < 0.01 **!, < 0.05 *!, < 0.1 !.

"1994-01-01 GMT" to "1994-12-31 GMT"

Shannon's entropy on 8 cores with 100 shuffles.

x and y have length 8760 (0 NAs removed)

[calculate] X->Y transfer entropy

[calculate] Y->X transfer entropy

[bootstrap] 300 times

Done - Total time 25.29 seconds

Shannon Transfer Entropy Results:

| Direction | TE | Eff. TE | Std.Err. | p-value | sig |
|-----------|----|---------|----------|---------|-----|
|-----------|----|---------|----------|---------|-----|

| | | | | | |
|------|--------|--------|--------|--------|-----|
| X->Y | 0.0173 | 0.0130 | 0.0007 | 0.0000 | *** |
| Y->X | 0.0051 | 0.0010 | 0.0008 | 0.4700 | |

Bootstrapped TE Quantiles (300 replications):

| | | | | | |
|-----------|----|-----|-----|-----|------|
| Direction | 0% | 25% | 50% | 75% | 100% |
|-----------|----|-----|-----|-----|------|

| | | | | | |
|------|--------|--------|--------|--------|--------|
| X->Y | 0.0031 | 0.0046 | 0.0051 | 0.0057 | 0.0075 |
| Y->X | 0.0031 | 0.0043 | 0.0048 | 0.0053 | 0.0069 |

Number of Observations: 8760

p-values: < 0.001 '***', < 0.01 '**', < 0.05 *', < 0.1 '.'

"1995-01-01 GMT" to "1995-12-31 GMT"

Shannon's entropy on 8 cores with 100 shuffles.

x and y have length 8760 (0 NAs removed)

[calculate] X->Y transfer entropy

[calculate] Y->X transfer entropy

[bootstrap] 300 times

Done - Total time 25.47 seconds

Shannon Transfer Entropy Results:

| | | | | | |
|-----------|----|---------|----------|---------|-----|
| Direction | TE | Eff. TE | Std.Err. | p-value | sig |
|-----------|----|---------|----------|---------|-----|

| | | | | | |
|------|--------|--------|--------|--------|-----|
| X->Y | 0.0244 | 0.0200 | 0.0007 | 0.0000 | *** |
| Y->X | 0.0088 | 0.0050 | 0.0008 | 0.0000 | *** |

Bootstrapped TE Quantiles (300 replications):

| | | | | | |
|-----------|----|-----|-----|-----|------|
| Direction | 0% | 25% | 50% | 75% | 100% |
|-----------|----|-----|-----|-----|------|

| | | | | | |
|------|--------|--------|--------|--------|--------|
| X->Y | 0.0031 | 0.0045 | 0.0050 | 0.0056 | 0.0075 |
| Y->X | 0.0030 | 0.0043 | 0.0048 | 0.0053 | 0.0069 |

Number of Observations: 8760

p-values: < 0.001 '***', < 0.01 '**', < 0.05 *', < 0.1 '.'

"1996-01-01 GMT" to "1996-12-31 GMT"

Shannon's entropy on 8 cores with 100 shuffles.

x and y have length 8784 (0 NAs removed)

[calculate] X->Y transfer entropy

[calculate] Y->X transfer entropy

[bootstrap] 300 times

Done - Total time 25.35 seconds

Shannon Transfer Entropy Results:

| Direction | TE | Eff. TE | Std.Err. | p-value | sig |
|-----------|--------|---------|----------|---------|-----|
| X->Y | 0.0240 | 0.0197 | 0.0008 | 0.0000 | *** |
| Y->X | 0.0088 | 0.0049 | 0.0007 | 0.0000 | *** |

Bootstrapped TE Quantiles (300 replications):

| Direction | 0% | 25% | 50% | 75% | 100% |
|-----------|--------|--------|--------|--------|--------|
| X->Y | 0.0034 | 0.0044 | 0.0049 | 0.0055 | 0.0069 |
| Y->X | 0.0032 | 0.0043 | 0.0047 | 0.0054 | 0.0073 |

Number of Observations: 8784

p-values: < 0.001 '***', < 0.01 '**', < 0.05 *', < 0.1 '.'

"1997-01-01 GMT" to "1997-12-31 GMT"

Shannon's entropy on 8 cores with 100 shuffles.

x and y have length 8760 (0 NAs removed)

[calculate] X->Y transfer entropy

[calculate] Y->X transfer entropy

[bootstrap] 300 times

Done - Total time 25.18 seconds

Shannon Transfer Entropy Results:

| Direction | TE | Eff. TE | Std.Err. | p-value | sig |
|-----------|--------|---------|----------|---------|-----|
| X->Y | 0.0105 | 0.0060 | 0.0007 | 0.0000 | *** |
| Y->X | 0.0054 | 0.0012 | 0.0008 | 0.4400 | |

Bootstrapped TE Quantiles (300 replications):

| Direction | 0% | 25% | 50% | 75% | 100% |
|-----------|--------|--------|--------|--------|--------|
| X->Y | 0.0033 | 0.0047 | 0.0052 | 0.0057 | 0.0080 |
| Y->X | 0.0030 | 0.0043 | 0.0048 | 0.0052 | 0.0072 |

Number of Observations: 8760

p-values: < 0.001 '***', < 0.01 '**', < 0.05 *', < 0.1 '.'

"1998-01-01 GMT" to "1998-12-31 GMT"

Shannon's entropy on 8 cores with 100 shuffles.

x and y have length 8760 (0 NAs removed)

[calculate] X->Y transfer entropy

[calculate] Y->X transfer entropy

[bootstrap] 300 times

Done - Total time 25.19 seconds

Shannon Transfer Entropy Results:

| Direction | TE | Eff. TE | Std.Err. | p-value | sig |
|-----------|--------|---------|----------|---------|-----|
| X->Y | 0.0199 | 0.0156 | 0.0008 | 0.0000 | *** |
| Y->X | 0.0083 | 0.0045 | 0.0007 | 0.0000 | *** |

Bootstrapped TE Quantiles (300 replications):

| Direction | 0% | 25% | 50% | 75% | 100% |
|-----------|--------|--------|--------|--------|--------|
| X->Y | 0.0029 | 0.0044 | 0.0049 | 0.0054 | 0.0072 |
| Y->X | 0.0028 | 0.0044 | 0.0048 | 0.0054 | 0.0075 |

Number of Observations: 8760

p-values: < 0.001 '***', < 0.01 '**', < 0.05 *', < 0.1 '.'

"1999-01-01 GMT" to "1999-12-31 GMT"

Shannon's entropy on 8 cores with 100 shuffles.

x and y have length 8760 (0 NAs removed)

[calculate] X->Y transfer entropy

[calculate] Y->X transfer entropy

[bootstrap] 300 times

Done - Total time 25.24 seconds

Shannon Transfer Entropy Results:

| Direction | TE | Eff. TE | Std.Err. | p-value | sig |
|-----------|--------|---------|----------|---------|-----|
| X->Y | 0.0193 | 0.0151 | 0.0008 | 0.0000 | *** |
| Y->X | 0.0066 | 0.0028 | 0.0008 | 0.0233 | * |

Bootstrapped TE Quantiles (300 replications):

| Direction | 0% | 25% | 50% | 75% | 100% |
|-----------|--------|--------|--------|--------|--------|
| X->Y | 0.0030 | 0.0044 | 0.0049 | 0.0054 | 0.0079 |
| Y->X | 0.0030 | 0.0042 | 0.0047 | 0.0052 | 0.0075 |

Number of Observations: 8760

p-values: < 0.001 '***', < 0.01 '**', < 0.05 *', < 0.1 '.'

"2000-01-01 GMT" to "2000-12-31 GMT"

Shannon's entropy on 8 cores with 100 shuffles.

x and y have length 8784 (0 NAs removed)

[calculate] X->Y transfer entropy

[calculate] Y->X transfer entropy

[bootstrap] 300 times

Done - Total time 25.12 seconds

Shannon Transfer Entropy Results:

| Direction | TE | Eff. TE | Std.Err. | p-value | sig |
|-----------|--------|---------|----------|---------|-----|
| X->Y | 0.0295 | 0.0255 | 0.0007 | 0.0000 | *** |
| Y->X | 0.0072 | 0.0031 | 0.0008 | 0.0133 | * |

Bootstrapped TE Quantiles (300 replications):

| Direction | 0% | 25% | 50% | 75% | 100% |
|-----------|--------|--------|--------|--------|--------|
| X->Y | 0.0035 | 0.0046 | 0.0052 | 0.0057 | 0.0080 |
| Y->X | 0.0029 | 0.0041 | 0.0047 | 0.0052 | 0.0069 |

Number of Observations: 8784

p-values: < 0.001 '***', < 0.01 '**', < 0.05 *', < 0.1 '.'

"2001-01-01 GMT" to "2001-12-31 GMT"

Shannon's entropy on 8 cores with 100 shuffles.

x and y have length 8760 (0 NAs removed)

[calculate] X->Y transfer entropy

[calculate] Y->X transfer entropy

[bootstrap] 300 times

Done - Total time 25.48 seconds

Shannon Transfer Entropy Results:

| Direction | TE | Eff. TE | Std.Err. | p-value | sig |
|-----------|--------|---------|----------|---------|-----|
| X->Y | 0.0202 | 0.0158 | 0.0007 | 0.0000 | *** |
| Y->X | 0.0090 | 0.0050 | 0.0008 | 0.0000 | *** |

Bootstrapped TE Quantiles (300 replications):

| Direction | 0% | 25% | 50% | 75% | 100% |
|-----------|--------|--------|--------|--------|--------|
| X->Y | 0.0030 | 0.0044 | 0.0050 | 0.0054 | 0.0076 |
| Y->X | 0.0030 | 0.0044 | 0.0048 | 0.0054 | 0.0069 |

Number of Observations: 8760

p-values: < 0.001 '***', < 0.01 '**', < 0.05 *', < 0.1 '.'

"2002-01-01 GMT" to "2002-12-31 GMT"

Shannon's entropy on 8 cores with 100 shuffles.

x and y have length 8760 (0 NAs removed)

[calculate] X->Y transfer entropy

[calculate] Y->X transfer entropy

[bootstrap] 300 times

Done - Total time 26.73 seconds

Shannon Transfer Entropy Results:

| Direction | TE | Eff. TE | Std.Err. | p-value | sig |
|-----------|--------|---------|----------|---------|-----|
| X->Y | 0.0150 | 0.0106 | 0.0008 | 0.0000 | *** |
| Y->X | 0.0097 | 0.0058 | 0.0008 | 0.0000 | *** |

Bootstrapped TE Quantiles (300 replications):

| Direction | 0% | 25% | 50% | 75% | 100% |
|-----------|----|-----|-----|-----|------|
|-----------|----|-----|-----|-----|------|

X->Y 0.0033 0.0044 0.0048 0.0053 0.0075

Y->X 0.0032 0.0042 0.0047 0.0053 0.0079

Number of Observations: 8760

p-values: < 0.001 '***', < 0.01 '**', < 0.05 *', < 0.1 '.'

"2003-01-01 GMT" to "2003-12-31 GMT"

Shannon's entropy on 8 cores with 100 shuffles.

x and y have length 8760 (0 NAs removed)

[calculate] X->Y transfer entropy

[calculate] Y->X transfer entropy

[bootstrap] 300 times

Done - Total time 25.62 seconds

Shannon Transfer Entropy Results:

| Direction | TE | Eff. TE | Std.Err. | p-value | sig |
|-----------|--------|---------|----------|---------|-----|
| X->Y | 0.0104 | 0.0060 | 0.0008 | 0.0000 | *** |
| Y->X | 0.0122 | 0.0083 | 0.0007 | 0.0000 | *** |

Bootstrapped TE Quantiles (300 replications):

| Direction | 0% | 25% | 50% | 75% | 100% |
|-----------|----|-----|-----|-----|------|
|-----------|----|-----|-----|-----|------|

X->Y 0.0031 0.0046 0.0050 0.0055 0.0070

Y->X 0.0031 0.0043 0.0048 0.0053 0.0081

Number of Observations: 8760

p-values: < 0.001 '***', < 0.01 '**', < 0.05 *', < 0.1 '.'

"2004-01-01 GMT" to "2004-12-31 GMT"

Shannon's entropy on 8 cores with 100 shuffles.

x and y have length 8784 (0 NAs removed)

[calculate] X->Y transfer entropy

[calculate] Y->X transfer entropy

[bootstrap] 300 times

Done - Total time 25.18 seconds

Shannon Transfer Entropy Results:

| Direction | TE | Eff. TE | Std.Err. | p-value | sig |
|-----------|--------|---------|----------|---------|-----|
| X->Y | 0.0161 | 0.0117 | 0.0008 | 0.0000 | *** |
| Y->X | 0.0120 | 0.0081 | 0.0008 | 0.0000 | *** |

Bootstrapped TE Quantiles (300 replications):

| Direction | 0% | 25% | 50% | 75% | 100% |
|-----------|--------|--------|--------|--------|--------|
| X->Y | 0.0030 | 0.0045 | 0.0049 | 0.0055 | 0.0075 |
| Y->X | 0.0031 | 0.0044 | 0.0048 | 0.0053 | 0.0086 |

Number of Observations: 8784

p-values: < 0.001 ***!, < 0.01 **!, < 0.05 *!, < 0.1 !

"2005-01-01 GMT" to "2005-12-31 GMT"

Shannon's entropy on 8 cores with 100 shuffles.

x and y have length 8760 (0 NAs removed)

[calculate] X->Y transfer entropy

[calculate] Y->X transfer entropy

[bootstrap] 300 times

Done - Total time 25.02 seconds

Shannon Transfer Entropy Results:

| Direction | TE | Eff. TE | Std.Err. | p-value | sig |
|-----------|--------|---------|----------|---------|-----|
| X->Y | 0.0145 | 0.0101 | 0.0007 | 0.0000 | *** |
| Y->X | 0.0099 | 0.0061 | 0.0008 | 0.0000 | *** |

Bootstrapped TE Quantiles (300 replications):

| Direction | 0% | 25% | 50% | 75% | 100% |
|-----------|--------|--------|--------|--------|--------|
| X->Y | 0.0030 | 0.0044 | 0.0049 | 0.0054 | 0.0079 |
| Y->X | 0.0030 | 0.0043 | 0.0049 | 0.0054 | 0.0072 |

Number of Observations: 8760

p-values: < 0.001 '***', < 0.01 '**', < 0.05 *', < 0.1 '.'

"2006-01-01 GMT" to "2006-12-31 GMT"

Shannon's entropy on 8 cores with 100 shuffles.

x and y have length 8760 (0 NAs removed)

[calculate] X->Y transfer entropy

[calculate] Y->X transfer entropy

[bootstrap] 300 times

Done - Total time 25.22 seconds

Shannon Transfer Entropy Results:

| Direction | TE | Eff. TE | Std.Err. | p-value | sig |
|-----------|--------|---------|----------|---------|-----|
| X->Y | 0.0087 | 0.0043 | 0.0008 | 0.0000 | *** |
| Y->X | 0.0091 | 0.0051 | 0.0008 | 0.0000 | *** |

Bootstrapped TE Quantiles (300 replications):

| Direction | 0% | 25% | 50% | 75% | 100% |
|-----------|--------|--------|--------|--------|--------|
| X->Y | 0.0032 | 0.0045 | 0.0050 | 0.0056 | 0.0077 |
| Y->X | 0.0026 | 0.0044 | 0.0049 | 0.0054 | 0.0073 |

Number of Observations: 8760

p-values: < 0.001 '***', < 0.01 '**', < 0.05 *', < 0.1 '.'

"2007-01-01 GMT" to "2007-12-31 GMT"

Shannon's entropy on 8 cores with 100 shuffles.

x and y have length 8760 (0 NAs removed)

[calculate] X->Y transfer entropy

[calculate] Y->X transfer entropy

[bootstrap] 300 times

Done - Total time 25.49 seconds

Shannon Transfer Entropy Results:

| Direction | TE | Eff. TE | Std.Err. | p-value | sig |
|-----------|--------|---------|----------|---------|-----|
| X->Y | 0.0215 | 0.0169 | 0.0008 | 0.0000 | *** |
| Y->X | 0.0066 | 0.0028 | 0.0008 | 0.0267 | * |

Bootstrapped TE Quantiles (300 replications):

| Direction | 0% | 25% | 50% | 75% | 100% |
|-----------|--------|--------|--------|--------|--------|
| X->Y | 0.0031 | 0.0043 | 0.0048 | 0.0054 | 0.0071 |
| Y->X | 0.0030 | 0.0043 | 0.0048 | 0.0053 | 0.0070 |

Number of Observations: 8760

p-values: < 0.001 '***', < 0.01 '**', < 0.05 *', < 0.1 '.'

"2008-01-01 GMT" to "2008-12-31 GMT"

Shannon's entropy on 8 cores with 100 shuffles.

x and y have length 8784 (0 NAs removed)

[calculate] X->Y transfer entropy

[calculate] Y->X transfer entropy

[bootstrap] 300 times

Done - Total time 26.03 seconds

Shannon Transfer Entropy Results:

| Direction | TE | Eff. TE | Std.Err. | p-value | sig |
|-----------|--------|---------|----------|---------|-----|
| X->Y | 0.0207 | 0.0163 | 0.0007 | 0.0000 | *** |
| Y->X | 0.0113 | 0.0075 | 0.0008 | 0.0000 | *** |

Bootstrapped TE Quantiles (300 replications):

| Direction | 0% | 25% | 50% | 75% | 100% |
|-----------|--------|--------|--------|--------|--------|
| X->Y | 0.0032 | 0.0045 | 0.0050 | 0.0055 | 0.0084 |
| Y->X | 0.0031 | 0.0042 | 0.0047 | 0.0052 | 0.0073 |

Number of Observations: 8784

p-values: < 0.001 '***', < 0.01 '**', < 0.05 *', < 0.1 '.'

"2009-01-01 GMT" to "2009-12-31 GMT"

Shannon's entropy on 8 cores with 100 shuffles.

x and y have length 8760 (0 NAs removed)

[calculate] X->Y transfer entropy

[calculate] Y->X transfer entropy

[bootstrap] 300 times

Done - Total time 26.25 seconds

Shannon Transfer Entropy Results:

| Direction | TE | Eff. TE | Std.Err. | p-value | sig |
|-----------|--------|---------|----------|---------|-----|
| X->Y | 0.0117 | 0.0071 | 0.0008 | 0.0000 | *** |
| Y->X | 0.0090 | 0.0047 | 0.0008 | 0.0000 | *** |

Bootstrapped TE Quantiles (300 replications):

| Direction | 0% | 25% | 50% | 75% | 100% |
|-----------|--------|--------|--------|--------|--------|
| X->Y | 0.0035 | 0.0045 | 0.0050 | 0.0056 | 0.0077 |

Y->X 0.0032 0.0044 0.0049 0.0054 0.0073

Number of Observations: 8760

p-values: < 0.001 '***', < 0.01 '**', < 0.05 *, < 0.1 .

"2010-01-01 GMT" to "2010-12-31 GMT"

Shannon's entropy on 8 cores with 100 shuffles.

x and y have length 8760 (0 NAs removed)

[calculate] X->Y transfer entropy

[calculate] Y->X transfer entropy

[bootstrap] 300 times

Done - Total time 25.76 seconds

Shannon Transfer Entropy Results:

| Direction | TE | Eff. TE | Std.Err. | p-value | sig |
|-----------|--------|---------|----------|---------|-----|
| X->Y | 0.0147 | 0.0103 | 0.0007 | 0.0000 | *** |
| Y->X | 0.0104 | 0.0066 | 0.0008 | 0.0000 | *** |

Bootstrapped TE Quantiles (300 replications):

| Direction | 0% | 25% | 50% | 75% | 100% |
|-----------|--------|--------|--------|--------|--------|
| X->Y | 0.0030 | 0.0045 | 0.0049 | 0.0056 | 0.0074 |
| Y->X | 0.0031 | 0.0044 | 0.0049 | 0.0054 | 0.0072 |

Number of Observations: 8760

p-values: < 0.001 '***', < 0.01 '**', < 0.05 *, < 0.1 .

"2011-01-01 GMT" to "2011-12-31 GMT"

Shannon's entropy on 8 cores with 100 shuffles.

x and y have length 8760 (0 NAs removed)

[calculate] X->Y transfer entropy

[calculate] Y->X transfer entropy

[bootstrap] 300 times

Done - Total time 24.91 seconds

Shannon Transfer Entropy Results:

| Direction | TE | Eff. TE | Std.Err. | p-value | sig |
|-----------|--------|---------|----------|---------|-----|
| X->Y | 0.0122 | 0.0076 | 0.0008 | 0.0000 | *** |
| Y->X | 0.0078 | 0.0041 | 0.0007 | 0.0000 | *** |

Bootstrapped TE Quantiles (300 replications):

| Direction | 0% | 25% | 50% | 75% | 100% |
|-----------|----|-----|-----|-----|------|
| | | | | | |

X->Y 0.0030 0.0045 0.0050 0.0054 0.0071
Y->X 0.0031 0.0045 0.0049 0.0055 0.0074

Number of Observations: 8760

p-values: < 0.001 '***', < 0.01 '**', < 0.05 *', < 0.1 '.'

"2012-01-01 GMT" to "2012-12-31 GMT"

Shannon's entropy on 8 cores with 100 shuffles.

x and y have length 8784 (0 NAs removed)

[calculate] X->Y transfer entropy

[calculate] Y->X transfer entropy

[bootstrap] 300 times

Done - Total time 25.66 seconds

Shannon Transfer Entropy Results:

| Direction | TE | Eff. TE | Std.Err. | p-value | sig |
|-----------|--------|---------|----------|---------|-----|
| X->Y | 0.0114 | 0.0070 | 0.0008 | 0.0000 | *** |
| Y->X | 0.0103 | 0.0064 | 0.0007 | 0.0000 | *** |

Bootstrapped TE Quantiles (300 replications):

| Direction | 0% | 25% | 50% | 75% | 100% |
|-----------|--------|--------|--------|--------|--------|
| X->Y | 0.0032 | 0.0044 | 0.0049 | 0.0054 | 0.0074 |
| Y->X | 0.0031 | 0.0043 | 0.0048 | 0.0054 | 0.0074 |

Number of Observations: 8784

p-values: < 0.001 '***', < 0.01 '**', < 0.05 *', < 0.1 '.'

"2013-01-01 GMT" to "2013-12-31 GMT"

Shannon's entropy on 8 cores with 100 shuffles.

x and y have length 8760 (0 NAs removed)

[calculate] X->Y transfer entropy

[calculate] Y->X transfer entropy

[bootstrap] 300 times

Done - Total time 24.85 seconds

Shannon Transfer Entropy Results:

| Direction | TE | Eff. TE | Std.Err. | p-value | sig |
|-----------|--------|---------|----------|---------|-----|
| X->Y | 0.0130 | 0.0085 | 0.0008 | 0.0000 | *** |
| Y->X | 0.0073 | 0.0031 | 0.0008 | 0.0100 | * |

Bootstrapped TE Quantiles (300 replications):

| Direction | 0% | 25% | 50% | 75% | 100% |
|-----------|----|-----|-----|-----|------|
|-----------|----|-----|-----|-----|------|

| | | | | | |
|------|--------|--------|--------|--------|--------|
| X->Y | 0.0031 | 0.0046 | 0.0051 | 0.0057 | 0.0081 |
| Y->X | 0.0032 | 0.0043 | 0.0048 | 0.0053 | 0.0071 |

Number of Observations: 8760

p-values: < 0.001 '***', < 0.01 '**', < 0.05 *, < 0.1 .

"2014-01-01 GMT" to "2014-12-31 GMT"

Shannon's entropy on 8 cores with 100 shuffles.

x and y have length 8760 (0 NAs removed)

[calculate] X->Y transfer entropy

[calculate] Y->X transfer entropy

[bootstrap] 300 times

Done - Total time 24.87 seconds

Shannon Transfer Entropy Results:

| Direction | TE | Eff. TE | Std.Err. | p-value | sig |
|-----------|----|---------|----------|---------|-----|
|-----------|----|---------|----------|---------|-----|

| | | | | | |
|------|--------|--------|--------|--------|-----|
| X->Y | 0.0172 | 0.0129 | 0.0007 | 0.0000 | *** |
| Y->X | 0.0094 | 0.0055 | 0.0007 | 0.0000 | *** |

Bootstrapped TE Quantiles (300 replications):

| Direction | 0% | 25% | 50% | 75% | 100% |
|-----------|----|-----|-----|-----|------|
|-----------|----|-----|-----|-----|------|

| | | | | | |
|------|--------|--------|--------|--------|--------|
| X->Y | 0.0032 | 0.0044 | 0.0048 | 0.0053 | 0.0076 |
| Y->X | 0.0029 | 0.0043 | 0.0048 | 0.0053 | 0.0072 |

Number of Observations: 8760

p-values: < 0.001 '***', < 0.01 '**', < 0.05 *, < 0.1 .

"2015-01-01 GMT" to "2015-12-31 GMT"

Shannon's entropy on 8 cores with 100 shuffles.

x and y have length 8760 (0 NAs removed)

[calculate] X->Y transfer entropy

[calculate] Y->X transfer entropy

[bootstrap] 300 times

Done - Total time 24.91 seconds

Shannon Transfer Entropy Results:

| Direction | TE | Eff. TE | Std.Err. | p-value | sig |
|-----------|----|---------|----------|---------|-----|
|-----------|----|---------|----------|---------|-----|

| | | | | | |
|------|--------|--------|--------|--------|-----|
| X->Y | 0.0088 | 0.0043 | 0.0007 | 0.0000 | *** |
| Y->X | 0.0065 | 0.0030 | 0.0008 | 0.0100 | * |

Bootstrapped TE Quantiles (300 replications):

Direction 0% 25% 50% 75% 100%

X->Y 0.0031 0.0043 0.0048 0.0053 0.0078

Y->X 0.0029 0.0043 0.0048 0.0053 0.0071

Number of Observations: 8760

p-values: < 0.001 '***', < 0.01 '**', < 0.05 *', < 0.1 '.'

"2016-01-01 GMT" to "2016-12-31 GMT"

Shannon's entropy on 8 cores with 100 shuffles.

x and y have length 8784 (0 NAs removed)

[calculate] X->Y transfer entropy

[calculate] Y->X transfer entropy

[bootstrap] 300 times

Done - Total time 25.46 seconds

Shannon Transfer Entropy Results:

Direction TE Eff. TE Std.Err. p-value sig

X->Y 0.0184 0.0140 0.0008 0.0000 ***

Y->X 0.0084 0.0047 0.0008 0.0000 ***

Bootstrapped TE Quantiles (300 replications):

Direction 0% 25% 50% 75% 100%

X->Y 0.0032 0.0043 0.0048 0.0054 0.0074

Y->X 0.0032 0.0044 0.0049 0.0055 0.0074

Number of Observations: 8784

p-values: < 0.001 '***', < 0.01 '**', < 0.05 *', < 0.1 '.'

"2017-01-01 GMT" to "2017-12-31 GMT"

Shannon's entropy on 8 cores with 100 shuffles.

x and y have length 8760 (0 NAs removed)

[calculate] X->Y transfer entropy

[calculate] Y->X transfer entropy

[bootstrap] 300 times

Done - Total time 24.96 seconds

Shannon Transfer Entropy Results:

Direction TE Eff. TE Std.Err. p-value sig

X->Y 0.0170 0.0125 0.0008 0.0000 ***
Y->X 0.0083 0.0044 0.0008 0.0000 ***

Bootstrapped TE Quantiles (300 replications):

Direction 0% 25% 50% 75% 100%

X->Y 0.0034 0.0045 0.0050 0.0056 0.0076
Y->X 0.0031 0.0043 0.0048 0.0053 0.0074

Number of Observations: 8760

p-values: < 0.001 '***', < 0.01 '**', < 0.05 *, < 0.1 .